NWRF 15-0763-076

OCCURRENCE AND CAUSES OF HIGH-LEVEL TURBULENCE

FINAL REPORT

Submitted to:

Officer-in-Charge
Navy Weather Research Facility
Naval Air Station
Norfolk 11, Virginia

Contract Number: N 189(188) 55120 A

Project Leader: Elmar R. Reiter

Technical Paper No. 45
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

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ABSTRACT

The research reported in this paper has been conducted during the period 15 June 1961 to 15 July 1963. The project has been organized in three phases:

1. Photographic field measurement program.
2. Aircraft measurements.
3. Synoptic and theoretical studies on clear-air turbulence (CAT) and atmospheric mesostructure.

The research results of this project have been published in the reports listed in the references (1 through 15).

This final report summarizes the findings and states recommendations as to application of results and areas of future research.

Summary of Research Results

The research area has been subdivided into three phases:

1. Photographic field measurement program
2. Aircraft measurements
3. Synoptic and theoretical studies on clear-air turbulence (CAT) and atmospheric mesostructure

1. Photographic field measurement program

A set of two K-24 aerial photography cameras were mounted on transits and were adapted for cloud photogrammetry work (2, 14). Enough evidence could be collected from photographs of wave-clouds at cirrus level to prove, that short-lived and transient wave disturbances of wave-lengths of the order of magnitude of 10^2m are present in the upper troposphere and lower stratosphere (1, 5, 6, 7, 8, 10). These waves would have the right wave lengths and sufficient amplitude to produce "cobble-stone" CAT where they were encountered by a fast flying jet aircraft in clear air.

It proved to be difficult to photograph wave clouds of short "CAT" wave lengths in "statu nascendi". Most of the wave clouds observed did not show any significant changes in their structure and merely were drifting downstream with the prevailing wind. They constituted "frozen images" of perturbations that occurred earlier and farther upstream. Only on rare occasions would time-lapse photography reveal such wave formations in the making. The relative sparse occurrence of such waves in the forming stage ties in well with the patchiness of CAT observations.

In the course of the last year the photogrammetry project has been modified in order to study detailed vertical wind profiles by photographical balloon tracking (14). Considerable effort went into this endeavor. The results were only in part positive, because the optical resolution of the system in use did not suffice to permit effective tracking of the balloons to greater heights.

2. Aircraft measurements

Two research flights were conducted in the Rocky Mountain region by the Navy A-3-D aircraft on May 10 and 11, 1962, operating from Colorado Springs. Due to instrument failure these two missions could be considered only in part successful.

A joint flight measurement program which was conducted during February and March 1962 with the Navy A-3-D, and with the specially instrumented DC-6 and B-57 of the Weather Bureau's Hurricane Research Flight Facility proved to be more successful. Especially useful were the comparisons between radar and pressure altitude which could be obtained on several flights off the United States east coast. The data from these research flights are presently being analyzed by Mr. Davis and Mr. Anderson, both working under a Link Foundation Fellowship. Reports on this analysis work will be forthcoming (15).

3. Synoptic and theoretical studies on clear-air turbulence (CAT) and atmospheric mesostructure

CAT seems to occur at all levels of the atmosphere presently used by aviation (7). In the upper troposphere and stratosphere CAT is mainly associated with stable thermal stratification and with vertical wind shears. Convective motions, therefore, cannot serve as an explanation of the physical causes of CAT at these levels.

From cloud photography, as mentioned earlier, it became evident, that wave perturbations of a wide spectrum range of wave lengths may exist at upper tropospheric and stratospheric levels (4). These perturbations at times may be strong enough to cause serious difficulties to aircraft operations (3, 11). They may be caused orographically, which accounts for the relatively large incidence of CAT cases over the Rocky Mountains and Alleghenies. In cases of CAT occurrence over the Midwestern plains frontal systems and pressure jump lines were found to provide a possible source of perturbation energy. A detailed report on these studies is in preparation (13).

It was also found, that the entrance regions of strong jet maxima which are located at, or not far downstream from, a trough show relatively large frequencies of CAT occurrence. Usually one finds two or more "jet fingers" merging in these entrance regions: one coming from the northwest, another from the southwest.

Detailed analyses of isentropic streamline patterns, of cross-sections and of pilot reports revealed that in these entrance regions the northern jet branch actually dips underneath the southern branch. The cold advection associated with this flow pattern at tropopause level brings about stabilization of the atmospheric layers between the two jet stream branches. This may account for the presence of an extremely sharp developed "jet stream front" farther downstream, where the two jet branches have already merged into one jet maximum.

Cross-sections drawn through these entrance regions of jet maxima with CAT may not reveal much of a vertical scalar wind shear. Due to the sharp turning of wind with height the transition zone between the northern and the southern jet finger, where most of the CAT seems to occur, is marked by a strong vector wind shear, however (13).

Pilot reports on CAT and upper winds as transmitted over the standard teletype sequences usually show much more detail in the wind field at jet stream level than is apparent from rawinsonde observations. Time continuity in these details proves their physical reality. Some of these mesostructural details seem to be tied in with CAT occurrence (13).

That some of the atmospheric mesostructure is rather long-lived and apparently is not dissipated rapidly by mixing processes became evident from detailed trajectory analyses of a radioactive debris cloud. This cloud could be followed within a stable layer from Flin Flon, Canada, where it was encountered by a scintillation sonde on September 15, 1961, near the 700 mb level, to the United States East Coast, where it reached the ground in heavy radioactive fallout two days later. The debris probably originated near tropopause level from the Soviet test of September 10, 1961, over Novaya Zemlya (9, 12).

The existence of a well pronounced vertical circulation pattern around the jet stream could be derived from this case study. Sinking motion and intrusion of stratospheric air into the troposphere occur in a narrow channel along the jet axis. Air masses following this sinking motion retain their absolute potential vorticity, even though they are crossing the location of the jet axis from the cyclonic to the anticyclonic side. They do this by "slipping through" underneath the jet axis within the stable layer of the jet stream front. Thus, the theorem of conservation of potential vorticity is not violated by this motion.

Application of Research Results and Areas of Future Research

As a main result of this investigation the fact has been established that CAT may be frequently associated with stable stratifications in the atmosphere. Depending on the amount of perturbation energy available (due to orographic and other effects) and on the degree of dynamic instability present in the atmosphere (as for instance, expressed by Richardson's number), we will have to expect a more or less rapidly decaying wave motion along stable interfaces as a significant source of CAT occurrence.

This conclusion offers two major fields of application which deserve further investigation.

1. Forecasting CAT for present type aircraft.
2. Extrapolation of CAT expectancy for future type aircraft.

The correlation of CAT with stable layers, specifically with those showing marked vertical vector wind shears, makes it feasible to forecast this phenomenon. Especially the occurrence of severe and moderate CAT in the entrance region of a jet maximum (13) should not be too difficult to foresee even from our present radiosonde network. More detailed knowledge of the mesostructure of wind and temperature fields in the upper troposphere and lower stratosphere will be required, however, before CAT forecasting can become highly effective. Carefully planned research flights with specially instrumented aircraft will be necessary to study the behavior in space and time of such mesostructural details in winds and temperatures which are associated with CAT.

Extrapolation of CAT expectancy to future type aircraft still remains a highly disputed problem. From present evidence it appears, that stable layers associated with vertical vector-wind shear may be found rather frequently in the vicinity of the polar-night jet stream. U-2 data indicate a decrease of CAT frequency with increasing height beyond the tropopause (7). These data, however, have been collected with a subsonic aircraft, and therefore do not cover the spectral range of atmospheric perturbations that would affect a supersonic vehicle. Again, a field program is advocated, which will yield data on meso- and microstructural details at stratospheric levels especially in the vicinity of the polar-night jet stream where CAT-bearing perturbations are expected to reach their maximum intensity.

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